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RESEARCH MEMORANDUM

HEAT TRANSFER IN REGIONS OF SEPARATED AND REATTACHED FLOWS

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HEAT TRANSFER IN REGIONS OF SEPARATED AND REATTACHED FLOWS

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SUMMARY

Past experimental work has indicated that separated flow can greatly increase the heat transfer to a surface; whereas, some theoretical studies have indicated a possible decrease. Recent investigations have helped to clarify the effects of separation on heat transfer and have indicated a method of reducing separation. This paper considers the results of some of these investigations and shows the heat transfer in regions of separation and reattachment for a few specific shapes. These results show that the heat transfer in a separated region is strongly affected by the extent of separation, the location of the reattachment point, and the location of transition along the separated boundary.

INTRODUCTION

Recent experimental and theoretical investigations have shown that the separation of the boundary layer from a surface can have a great effect on the heat flow to the surface. At high altitudes and high Mach numbers, the presence of separation is more likely, and the regions of separation are more extensive because of the thicker boundary layers characteristic of this type of flight. Past experimental work has indicated that separated flow can greatly increase the heat transfer to a surface (ref. 1), whereas some theoretical studies have indicated a possible decrease (ref. 2). Recent investigations have helped to clarify the effects of separation on heat transfer and have indicated a method of reducing separation. This paper considers the results of some of these investigations and shows the heat transfer in regions of separation and reattachment for a few specific shapes. For one of these shapes, boundary-layer bleed was used to delay separation and to alter the heat transfer in the region of possible separation.

[redacted]

b distance along surface from zero station to sphere-cylinder juncture

C_D drag coefficient

d diameter of vehicle at characteristic station, as indicated in figures

l length

M Mach number

N_{St} Stanton number

q heat transfer per unit area per unit time

$q_{0,ns}$ heat transfer per unit area per unit time at zero station with no spike

R Reynolds number based on characteristic length along surface

R_d Reynolds number based on d

s distance along surface from zero station

x distance along axis of test vehicle, as indicated in figures

DISCUSSION

Flare Skirt

One interesting case of separation is the flow about an ogive-cylinder body with a 30° tail flare (ref. 3). The tail flare is a possible stabilizing device as well as a drag brake for many missile shapes. The lower curve of figure 1 shows the position of the start of separation as a function of Reynolds number. Figure 2 shows the approximate shape of the flow pattern for three Reynolds numbers. At low Reynolds numbers the start of separation moves forward slightly with increasing Reynolds number as is expected with laminar separation (ref. 4). The shape of the flow pattern when the separation is a maximum is shown in the top diagram of figure 2. As the Reynolds number increases, the boundary layer over the separated region tends to become transitional, which causes the position of the start of separation to move back along the model until at a Reynolds number of 0.5×10^6 the flow pattern appears as is shown in the center diagram of figure 2. At high Reynolds numbers, the boundary layer is fully turbulent ahead of the separation, as is shown in the lower diagram of figure 2, and this causes the flow to

be attached at the start of the flare. The Reynolds number range in these figures corresponds to that of a missile 50 feet long at an altitude of about 140,000 feet to 200,000 feet.

The upper curve of figure 1 shows the effect of separation upon the flare drag. At high Reynolds numbers where the flow is attached the pressure drag of the flare is slightly less than the drag predicted by wedge theory. As the Reynolds number decreases and the extent of separation becomes greater, the drag of the flare decreases to about one-tenth the drag predicted by wedge theory.

The heat transfer to this body when the Reynolds number is high enough to prevent separation is shown in figure 3. The heat-transfer coefficient used is based on the free-stream conditions ahead of the model and is thus approximately proportional to the actual heat transfer to the model when the model is at a constant temperature. The heat transfer to the forward part of the body, where the boundary layer is laminar, is in agreement with the laminar theory (ref. 5). After the start of transition at a value of x/d of approximately 7.5, the heat transfer increases rapidly. The heat transfer to the 30° flare is closely predicted by the turbulent theory (ref. 6) when it is assumed that the turbulent boundary layer starts at the beginning of the flare.

The effect of separation on the heat transfer to this same body may be seen by comparing figure 3 with figure 4 which shows the heat transfer to the body at a lower Reynolds number and with separation. In figure 4 it is seen that the heat transfer to the forward part is again closely predicted by laminar theory; however, under the separated boundary the heat transfer to the cylinder is below the attached laminar heat transfer at the increased pressure of the separated region as shown by the upper theoretical curve. The heat transfer is in reasonable agreement with the lower curve shown in this region, which is the prediction of Chapman's theory for separated laminar flow (ref. 2) and is 56 percent of the attached laminar theory. As the separated boundary layer becomes transitional, the heat transfer increases above the value expected for a laminar boundary layer. The heat transfer to the reattached boundary layer on the flare is again closely predicted by turbulent theory if the boundary layer is assumed to start at the reattachment point.

The heat transfer to a 10° tail flare following the same ogive-cylinder body was also tested at $M = 6.8$ (ref. 3). The separation effects were similar but much less predominant.

The investigation discussed so far has shown that some areas of the flare of this model are subjected to severe heating whether or not there are regions of separated flow. Since the flare will better provide drag if separation is prevented, a gap was provided at the start of the flare to act as a boundary-layer bleed. It was hoped that this gap would

prevent separation at a lower Reynolds number and would bleed off the turbulent boundary layer to allow the start of a laminar boundary layer at the start of the flare. The prevention of separation at a lower Reynolds number would increase the drag of the flare at a higher altitude and would improve the ratio of the flare drag to the heat transfer to the flare. Obtaining laminar attached flow to the flare, instead of turbulent attached flow, would further improve this ratio.

The data shown in figure 5 are the heat transfer to the flare with a gap as compared with the heat transfer without a gap. The edge of the flare was sharp as is shown in the sketch. The gap width was about 10 percent of the body diameter which in this case corresponds to $1\frac{1}{2}$ times the boundary-layer thickness just ahead of the gap. The Reynolds number was high enough to cause the flow to become transitional on the cylinder ahead of the flare, and the boundary layer was attached at the flare-cylinder juncture both with and without the gap. As previously shown, the heat-transfer data taken with no gap agree well with the turbulent theory (ref. 6) when the boundary layer is assumed to start at the beginning of the flare. The heat-transfer data taken with the boundary-layer bleed tend to agree with laminar theory (refs. 7 and 8) at the start of the flare but agree with turbulent theory (ref. 6) near the base. At this Reynolds number the level of heat transfer to the entire flare is reduced by the gap.

Figure 6 shows the comparison of the heat transfer to the flare for the same two gap conditions but for about one-half the Reynolds number. In this case the gap width was about equal to the boundary-layer thickness. At this Reynolds number, the flow separates from the cylinder when there is no gap, and the reattachment point is 1 diameter back from the start of the flare. The boundary layer is laminar at the separation point with transition on the separated boundary. The heat transfer increases toward the reattachment point and then agrees with the turbulent theory for a boundary layer starting at the reattachment point. With a gap, the boundary layer is swallowed and the separation is prevented. The data show that the heat transfer with a gap is reduced below the heat transfer without a gap except near the start of the flare and is in reasonable agreement with the laminar theory.

When the Reynolds number was further reduced by a factor of two, the gap width was about 75 percent of the boundary-layer thickness. In this case the extent of the separated region was reduced by the boundary-layer bleed, but separation was not prevented.

From the foregoing discussion, it appears that an adequate boundary-layer bleed at the start of the flare can be used to prevent separation at a lower Reynolds number and to increase the ratio of drag to heat transfer even when the bleed is unnecessary to prevent separation.

Thus, a boundary-layer bleed may be used effectively to increase the drag of flares on missiles at high altitudes.

Hemisphere Nose With Spike

Another example of separated-flow phenomena is seen in figure 7. In this case the heat flow to a hemisphere-cylinder body with a nose spike 4 body diameters in length was tested at different Reynolds numbers. The ratio of the heat flow at each station to the heat flow at the stagnation point without a spike has been plotted against the distance along the surface from the stagnation point. The heat flow without a spike is shown by the circular symbols (ref. 9). The heat transfer with a spike at the highest Reynolds number tested was decreased in the small area up to the 30° station on the hemisphere but was increased behind the 30° station and was increased back along the cylinder. The total heat transfer to the hemisphere nose was approximately twice the total heat transfer without a spike. The schlieren photographs indicated transition on the spike ahead of the separation point at a local free-stream Reynolds number of about 3×10^{6} based on the boundary-layer length to transition. When tested at the lowest Reynolds number, the heat transfer to the nose of the model was reduced by the spike, whereas the heat transfer to the rest of the model was relatively unchanged. The total heat transfer to the hemisphere nose in this case was roughly one-half the total heat transfer without a spike. The boundary layer in this case was laminar over the separated region and was laminar over the entire hemisphere-cylinder body. The local free-stream Reynolds number to the reattachment point in this case was about 0.6×10^{6} based on the boundary-layer length to reattachment and was about 1.1×10^{6} to the end of the cylinder.

Test results have been obtained for the model at intermediate Reynolds numbers and for shorter spikes. In some of these tests, transition took place along the boundary of separation at a local free-stream Reynolds number as low as 0.8×10^{6} based on the total length of the boundary layer and the local conditions for the cone of separation. This may be compared with transition on the solid boundary of the spike at a local Reynolds number of 3×10^{6}, thus indicating the reduced stability of the laminar boundary layer over a region of separation. For these intermediate Reynolds numbers the total aerodynamic heat transfer to the hemisphere varied between the values for the highest and lowest Reynolds numbers in a consistent manner.

Blunt Nose With Afterbody

Another important case of separation is that of the separation on the afterbody of a blunt shape. Figure 8 shows the heat transfer to the forebody and to the tail cone of the body in the form of free-stream

parameters. Since this model was sting supported, the flow pattern and, thus, the heat transfer in the separated region may be different from that experienced by a free-flying body. The results are shown for a smooth forebody and for a forebody with a ring of roughness. The data for the forebody without the roughness show reasonable agreement with the laminar theory (ref. 5). The heat transfer to the tail cone following a smooth forebody is about 1/200 the value at the stagnation point of the forebody at a Mach number of 6.8, and this of course is a strong function of the Mach number. With roughness, the values of the heat transfer are approximately doubled on the nose behind the roughness and are about that to be expected for turbulent flow. With the roughness the heat transfer to the tail cone is about 1/100 the stagnation-point value.

The heat transfer to this same model at $M = 2$ is shown in figure 9. The Reynolds number of this test was high enough to cause transition on the nose with a smooth forebody. It is seen that the heat transfer agrees well with laminar theory (ref. 10) near the stagnation point and with turbulent theory (ref. 6) farther back. At this Mach number the heat transfer to the tail cone under a turbulent separated boundary layer is slightly more than one-tenth the laminar-stagnation-point value.

Flat Plate With Stringers

Another interesting case of the effect of separated flow is shown in figure 10. This is a comparison of heat transfer from a separated turbulent boundary layer with that from an attached turbulent boundary layer. Chapman predicts (ref. 2) that in this case the separated flow should result in a large increase in the heat transfer in supersonic flow at least up to $M = 1.6$. Figure 10 shows the results of a test at a Mach number of 2 on a flat plate having transverse stringers which caused the turbulent boundary layer to have regions of separation. The Reynolds numbers were sufficiently high to insure the presence of a turbulent boundary layer. A similar test without stringers gave values of heat transfer in reasonable agreement with the turbulent flat-plate theory shown (ref. 6). The heat transfer on the plate between the stringers was not increased by the presence of turbulent separation or reattachment but seemed to be slightly reduced by the presence of the stringers. The heat transfer to the front of the stringers was about double the heat transfer to the plate between the stringers, whereas the heat transfer to the rear of the stringers was below the heat transfer to the plate.

CONCLUDING REMARKS

This paper has shown the effect of separation upon the heat transfer to areas of possible separation on a few specific aerodynamic shapes. These results have shown that the heat transfer in a separated region is strongly affected by the extent of separation, the location of the reattachment point, and the location of transition along the separated boundary.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 6, 1957.

REFERENCES

1. Stalder, Jackson R., and Nielsen, Helmer V.: Heat Transfer From a Hemisphere-Cylinder Equipped With Flow-Separation Spikes. NACA TN 3287, 1954.

2. Chapman, Dean R.: A Theoretical Analysis of Heat Transfer in Regions of Separated Flow. NACA TN 3792, 1956.

3. Becker, John V., and Korycinski, Peter F.: Heat Transfer and Pressure Distribution at a Mach Number of 6.8 on Bodies With Conical Flares and Extensive Flow Separation. NACA RM L56F22, 1956.

4. Gadd, G. E., Holder, D. W., and Regan, J. D.: An Experimental Investigation of the Interaction Between Shock Waves and Boundary Layers. Proc. Roy. Soc. (London), ser. A, vol. 226, no. 1165, Nov. 9, 1954, pp. 227-253.

5. Stine, Howard A., and Wanlass, Kent: Theoretical and Experimental Investigation of Aerodynamic-Heating and Isothermal Heat-Transfer Parameters on a Hemispherical Nose With Laminar Boundary Layer at Supersonic Mach Numbers. NACA TN 3344, 1954.

6. Van Driest, E. R.: The Turbulent Boundary Layer With Variable Prandtl Number. Rep. No. AL-1914, North American Aviation, Inc., Apr. 2, 1954.

7. Van Driest, E. R.: Investigation of Laminar Boundary Layer in Compressible Fluids Using the Crocco Method. NACA TN 2597, 1952.

8. Mangler, W.: Compressible Boundary Layers on Bodies of Revolution. Reps. and Translations No. 47, British M.A.P. Völkenrode, Mar. 15, 1946.

9. Crawford, Davis H., and McCauley, William D.: Investigation of the Laminar Aerodynamic Heat-Transfer Characteristics of a Hemisphere-Cylinder in the Langley 11-Inch Hypersonic Tunnel at a Mach Number of 6.8. NACA TN 3706, 1956.

10. Lees, Lester: Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Flight Speeds. Jet Propulsion, vol. 26, no. 4, Apr. 1956, pp. 259-269.

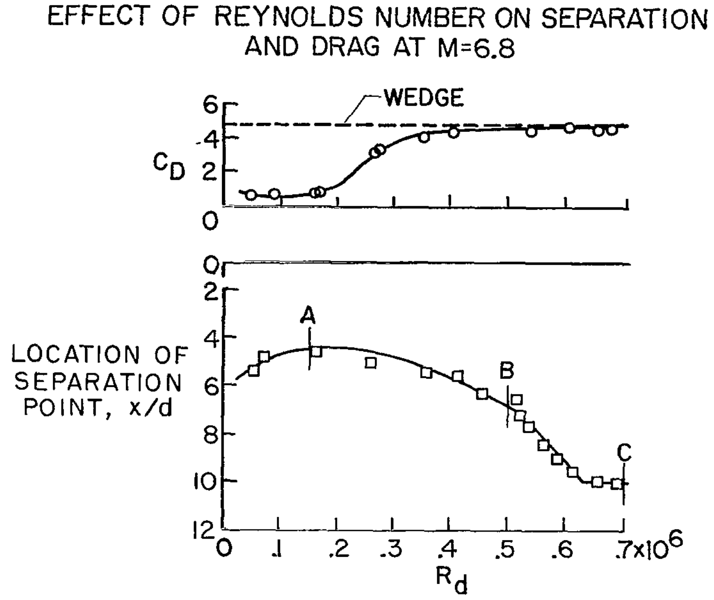

Figure 1

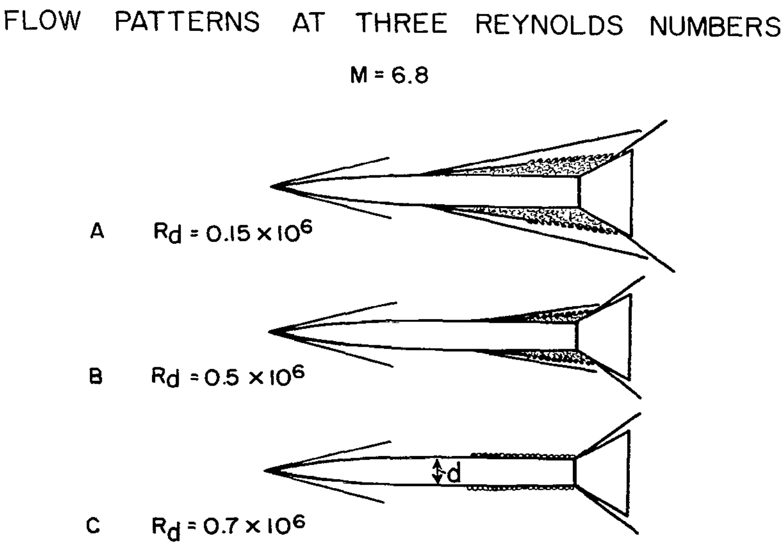

Figure 2

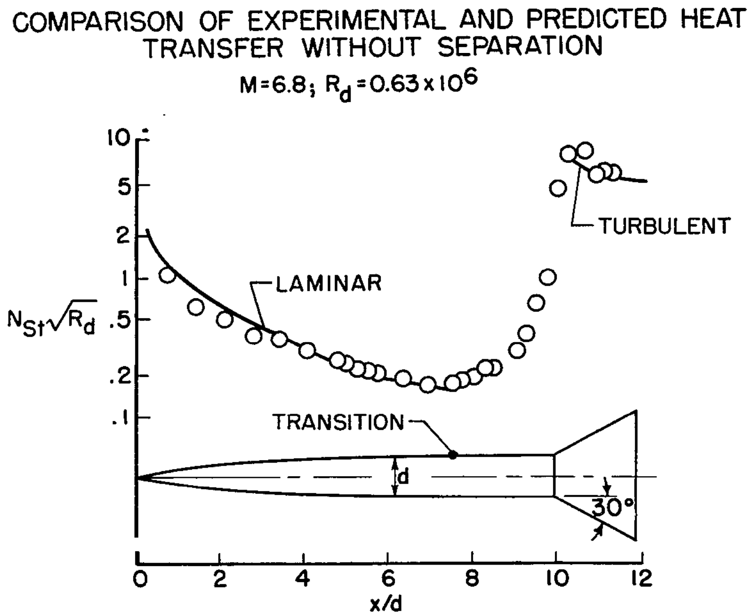

Figure 3

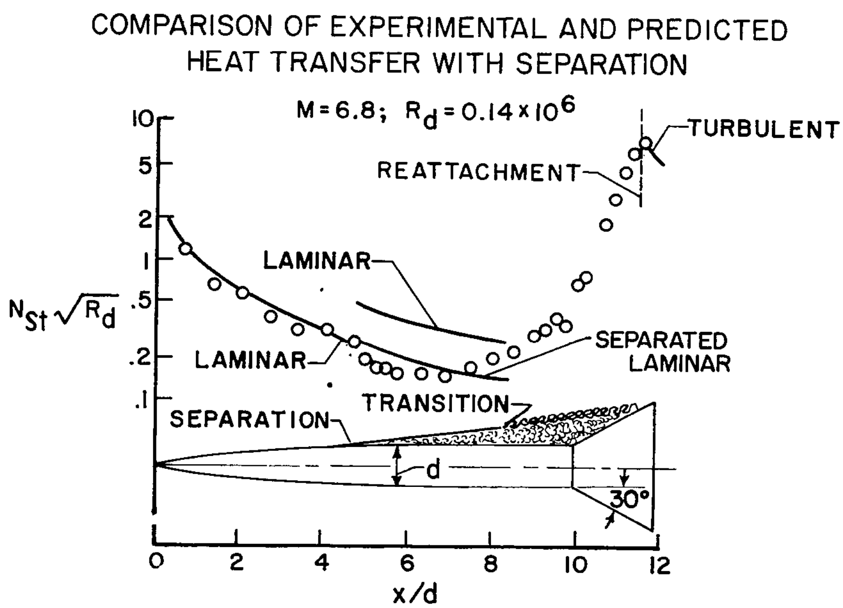

Figure 4

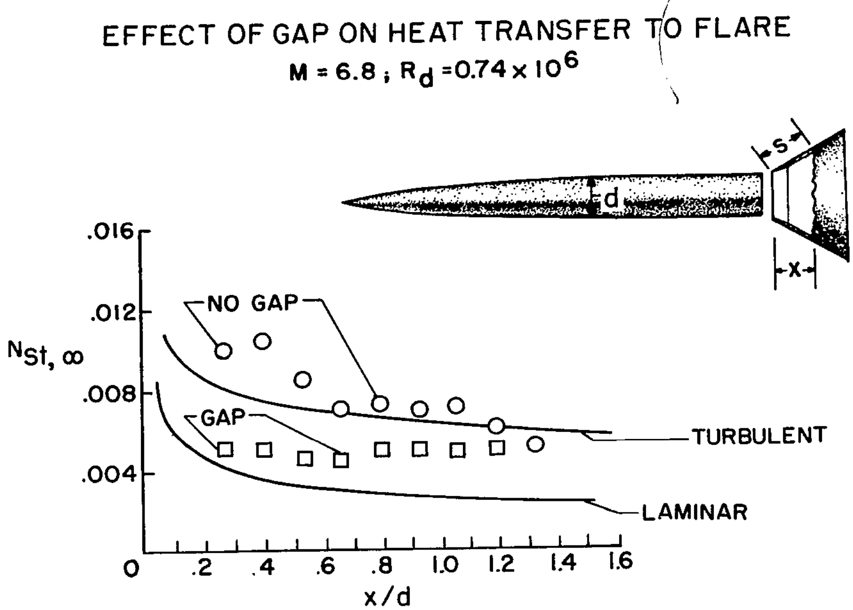

Figure 5

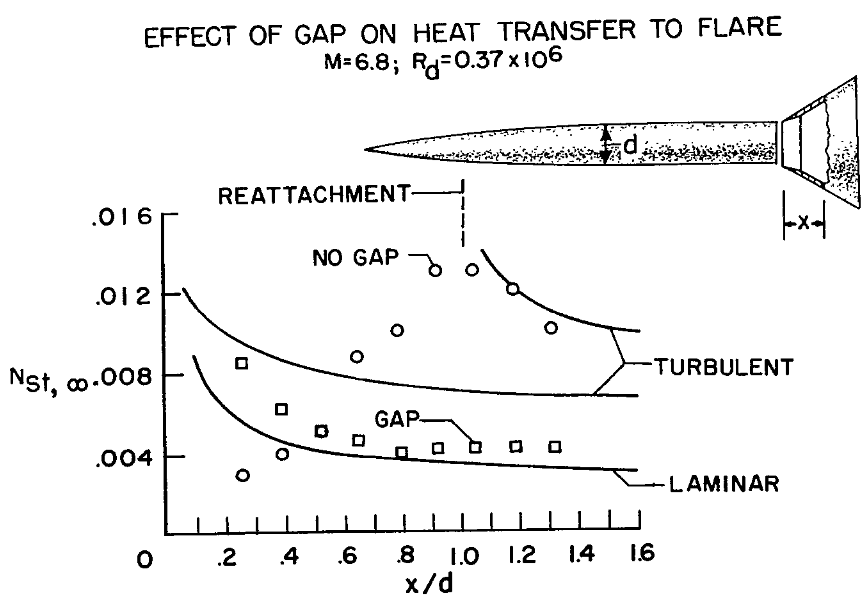

Figure 6

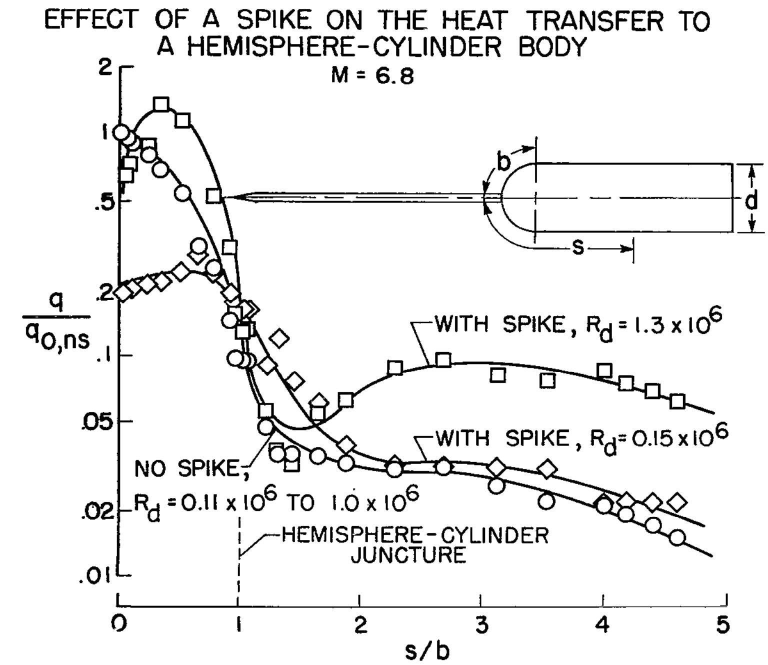

Figure 7

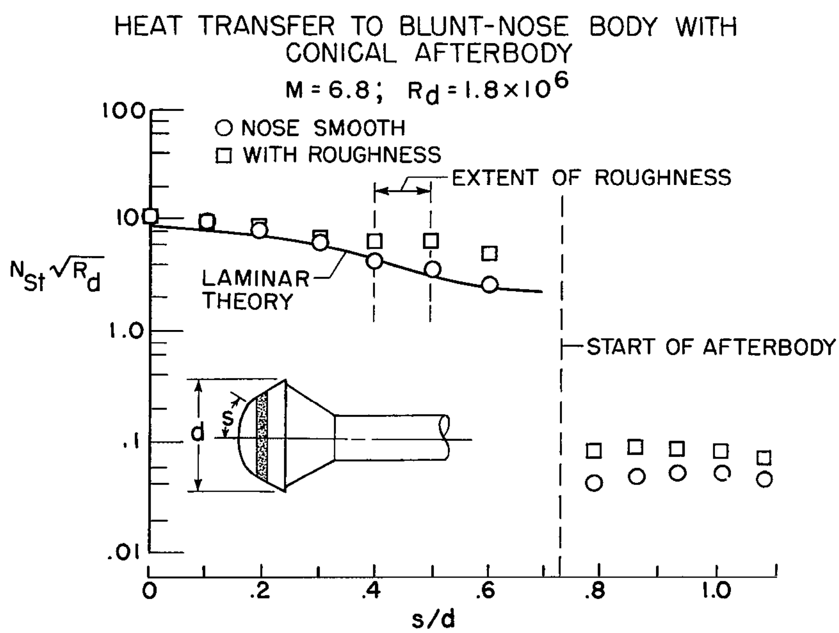

Figure 8

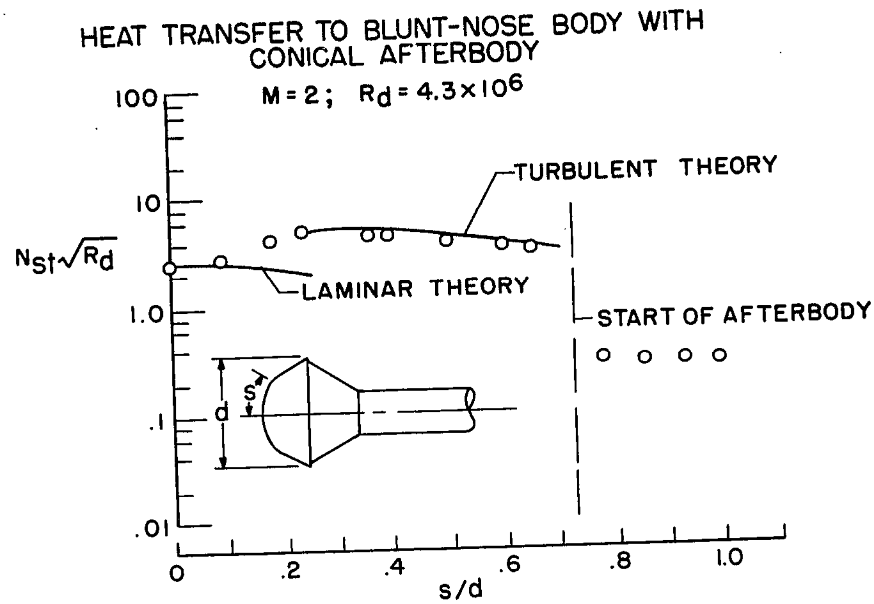

Figure 9

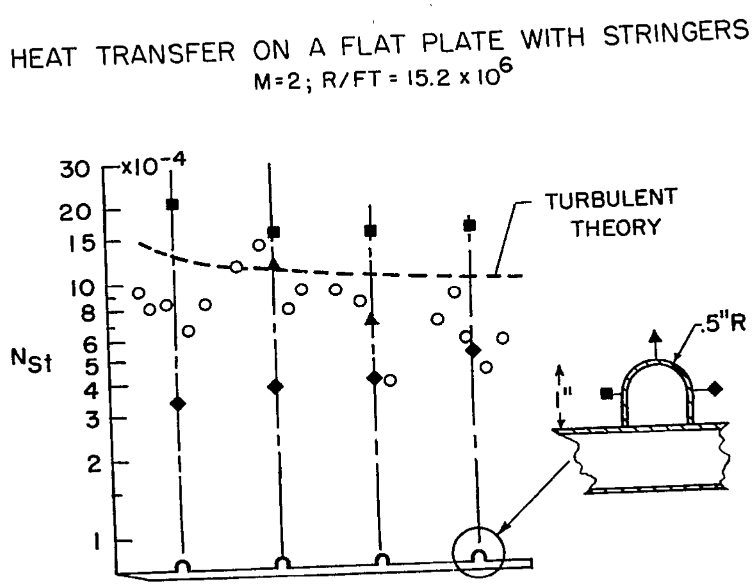

Figure 10